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Coverage comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km^2 area

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***Abstract*—In this simulation work the coverage of GPRS, Narrowband-IoT, LoRa, and SigFox is compared in a realistic scenario, covering 7800 km^2 and using Telenor's commercial 2G, 3G, and 4G deployment. The target is to evaluate which of the four technologies provides the best coverage for Internet of Things devices, which may be located deep indoor.**

The results show that Narrowband-IoT, having the best Maximum Coupling Loss performance of 164 dB, also provides the best coverage. This is despite the fact that LoRa and SigFox deployments with omnidirectional antennas are found to provide 3 dB lower link loss on average. In the deployment 11 % of the geographical area contains devices, located both in rural and urban areas. The NB-IoT has an outage below 1 % for locations experiencing 20 dB indoor penetration loss in addition to the outdoor path loss. SigFox performs similarly, while LoRa cannot provide coverage for 2 % of those locations. For the challenging deep indoor case, where 30 dB additional penetration loss is expected, NB-IoT has 8 % outage while SigFox and LoRa is unable to cover 13 % and 20 % of the locations.

The four technologies may not be deployed at all existing site locations and therefore the work also includes a study of the coverage as a function of the minimum Inter-Site Distance, where sites closer than 2, 4, and 6 km are filtered out. The results show that SigFox and NB-IoT have outage probabilities below 5 % even though sites closer than 4 km are removed from the simulations.

I. Introduction

In the next years the number of Internet of Things (IoT) devices is predicted to increase rapidly [1], and many of these Internet-connected devices will rely on a wireless connection. Therefore the 3GPP has recently standardized the LTE-M and Narrowband IoT (NB-IoT) updates in Long Term Evolution (LTE) release 13 to provide cellular connectivity for IoT. The targets are to ensure a device cost below 5 USD, uplink latency below 10 s, up to 40 connected devices per household, and a long battery life of 10 years [2]. Finally, the new LTE release 13 is also targeting a significant coverage improvement in order to support devices located deep indoor and in rural areas. Therefore, the Maximum Coupling Loss (MCL) for NB-IoT is 164 dB, which is a 20 dB improvement over GPRS [3]. A recent study even suggest NB-IoT performs well up to an MCL of 170 dB [4].

The IoT devices may not rely solely on cellular connectivity, but on Low Power Wide Area (LPWA) Radio Access Technology (RAT) and networks in general. The competitors to NB-IoT include LoRa [5], SigFox [6], and GPRS. The latter is a widely adopted solution due to its existing deployment in long-range sub-GHz bands and efficient transfer of the Short Message Service data, which is suitable for many types of low data rate IoT traffic.

In recent work the coverage and capacity has been studied for simple 3GPP deployments for NB-IoT [7] and LoRa [8]. In addition, [9] studied NB-IoT coverage and capacity for a small rural area with real operator-deployed base stations. However, to the best of the authors' knowledge there are no studies comparing the performance of the four key wireless IoT candidates in a realistic scenario. The contribution of this study is thus to analyze the coverage of GPRS, NB-IoT, LoRa, and SigFox in a realistic scenario, based on a 7800 km^2 terrain map combined with the configuration and location of the local operator Telenor's commercially deployed cellular sites. In addition the outage probability is studied as a function of the Inter-Site Distance (ISD), because all existing sites may not be upgraded with the new technologies.

The paper is structured as follows; in Section II the scenario and radio coverage simulation methodology is described, followed by the results in Section III. Finally, we present the discussion and the conclusion in Sections IV and V, respectively.

II. Radio Coverage Methodology

In this section we describe the radio coverage methodology and our simulation assumptions. The target is to study the coverage of the four RATs in a large area, consisting of both rural and urban sections, using the base station configuration of a commercially operating network and the MCL limits of each RAT as given in Table I, which is based on [3]. Furthermore, a sensitivity analysis of the ISD effect on the coverage is made, because all sites may not be upgraded. The analysis is based on ISD filtering, where a minimum ISD filter of 2, 4, or 6 km is used to remove sites that are closer than the current limit.

The area under study is the North Denmark region, which consists of 7800 km^2 of rural area, predominantly farm land, forests and smaller villages and a combined urban area of 147 km^2. The urban area is based on the city of Aalborg with 115k inhabitants and 9 other cities with 10-25k inhabitants each. The borders of the urban areas are defined as polygons using [10]. The site location and configuration is based on Telenor's commercial cellular network, consisting of 2G, 3G, and 4G deployments. Every 2G, 3G and 4G site, which currently is configured with a sub-GHz carrier has been included in the study, assuming that antennas and to some extent Radio Frequency hardware can be re-used if the site were to be

TABLE I
LOW POWER WIDE AREA RADIO TECHNOLOGIES. LINK SPECIFICS ARE GIVEN AS (UPLINK/DOWNLINK). BASED ON [3].

	GPRS	NB-IoT	LoRa	SigFox
Spectrum [MHz]	700-900	700-900	868	868
Band	Cellular, licensed	Cellular, licensed	ISM, unlicensed	ISM, unlicensed
Transmit power [dBm]	33/37	23/35	14	14/27
Bandwidth [kHz]	200	180	125	0.1/0.6
MCL [dB]	144	164	157	160

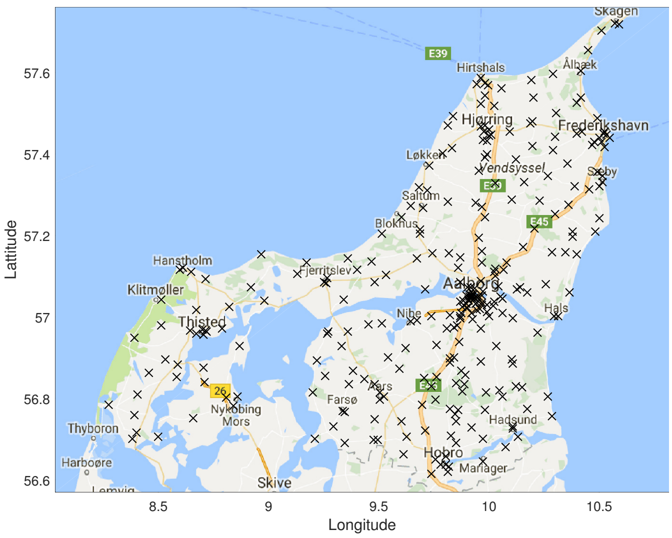

Fig. 1. Area under study, black crosses indicate a site location.

upgraded to NB-IoT. In total this results in 319 sites with 920 sectors in the North Denmark region area as illustrated in Fig. 1. Each sector has a directional antenna with an average beam width of 65 degrees, an average main beam gain of 17 dB, an average combined electrical and mechanical tilt of about 5 degrees, and an average height of 35 meters above the terrain. The LoRa and SigFox technologies do not rely on sectorized site deployments and thus Telenor's deployment configuration is modified such that every site applies a 10 dBi omni-directional antenna with a typical monopole radiation pattern. Due to this difference in base station configuration the propagation results are split into *cellular* (GPRS and NB-IoT) and *LPWA* (LoRa and SigFox) traces. Furthermore, the link budgets are different because the transmit power, given in Table I, of the cellular technologies is standardized to be the input to the antenna connector. As opposed to this the LoRa and SigFox transmit power is the power after the antenna connector that is the Effective Isotropically Radiated Power.

In order to perform realistic propagation modeling the area has been implemented in our calibrated MatLab simulator using the 3GPP Rural Macro non-line-of-sight (NLOS) model [11] for the rural areas and the 3GPP Urban Macro NLOS model [11] for the urban areas. In addition, shadow fading has been applied in accordance with [11], [12] as listed in the simulation assumptions in Table II. The propagation models utilize the free Danish Digital Height Model 2007 from [10],

TABLE II
SIMULATION ASSUMPTIONS.

Parameter	Urban	Rural
Scenario	Varying number of sites & sectors in 800 MHz band	
Antenna gain	Omni: 10 dB; directional: 17 dB (65° beam)	
Path Loss	Urban Macro NLOS	Rural Macro NLOS
Shadow fading	σ=6 dB	σ=8 dB
Correlation distance	50 m	1000 m
	sector correlation = 1, site correlation = 0.5	
Terrain map	Danish Digital Height Model 2007	
Map resolution	100 m x 100 m	
Indoor locations	All pixels	Based on OSM house numbers
Indoor loss	10, 20, 30 dB in addition to the outdoor path loss	

which has been scaled from 10 m resolution to 100 m in order to minimize the computational load. The 100 m x 100 m pixels constitute a grid with about 780k pixels. The height model is used to position the sites and the pixel locations relative to each other for accurate propagation modeling. The path loss from each sector is calculated per pixel after which the serving cell is selected based on the highest received power. In the urban areas each pixel is assumed to contain a device, which can be located both outdoor and indoor. The rural device locations are assigned to pixels, which according to the Open Street Maps database [13] have a valid house number. Similar to the urban area the device locations can be both outdoor and indoor. In total 9.6 % of the rural pixels have a house address which together with the urban area amounts to 11 % of all the 780k pixels. Since the IoT devices may be sensors located deep indoor the coverage study is performed for indoor locations by adding an additional penetration loss of 10, 20, or 30 dB to the estimated outdoor path loss as suggested in [12].

III. RESULTS

This section contains the simulated coverage performance, that is the geographical location availability probability, for GPRS, NB-IoT, LoRa, and SigFox using various minimum ISD filters.

Fig. 2 illustrates the Cumulative Distribution Function (CDF) of the minimum link loss (i.e. towards serving cell) at device locations in the 10 urban areas. The dashed vertical lines indicate the MCL of LoRa, SigFox, GPRS, and NB-IoT as defined in Table I. The part of the CDF to the left of a dashed line indicate the device locations which are in outage that is devices, which cannot be served by the technology due to the link loss exceeding the MCL. The outage percentage is defined in the figure if it is above 0.1 %. All technologies provide full outdoor coverage, while GPRS has 3 % outage for indoor device locations with 20 dB penetration loss due to the low MCL of 144 dB. The other RATs provide an outage below 1 % for the urban locations even in the deep indoor scenario with 30 dB additional penetration loss. The reason for the good coverage is the dense cell deployment.

The cell deployment is more sparse in the rural areas and therefore the outage probabilities increase as illustrated in Fig. 3, which shows the minimum link loss for cellular and LPWA device locations in the rural area. All outdoor locations are

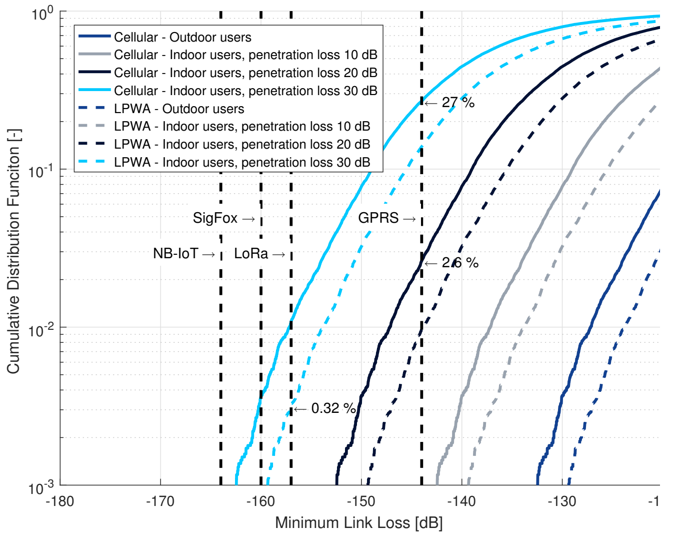

Fig. 2. MCL CDF for device locations in the urban areas with Telenor's original site deployment.

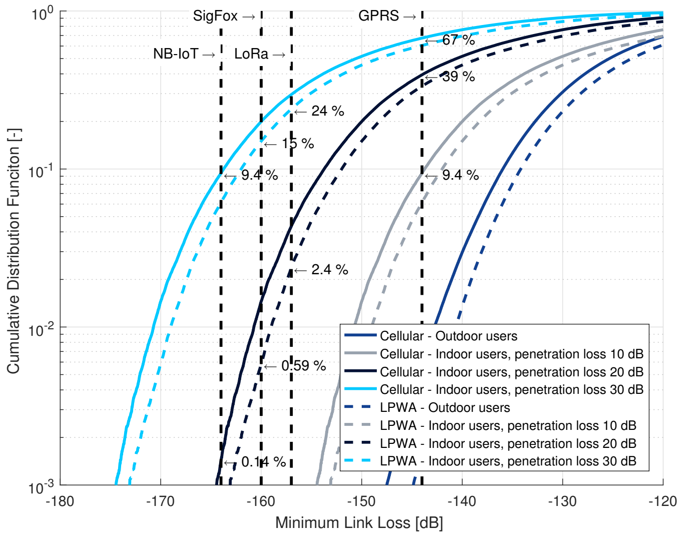

Fig. 3. MCL CDF for device locations in the rural areas with Telenor's original site deployment.

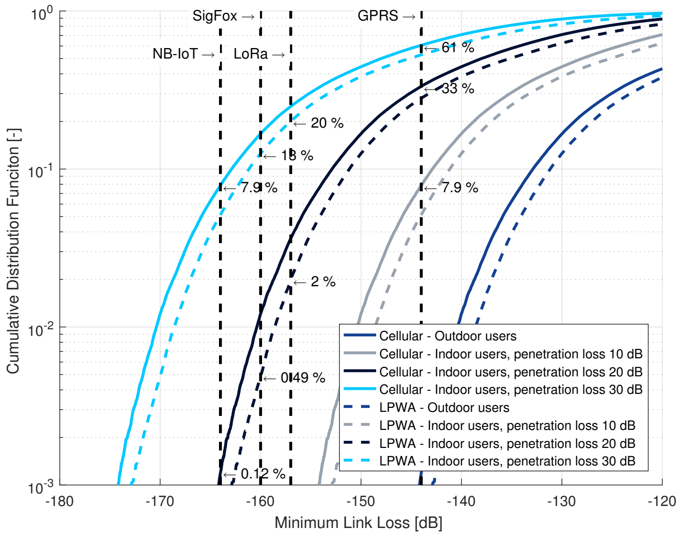

Fig. 4. MCL CDF for device locations in both the rural and urban areas with Telenor's original site deployment.

TABLE III
SITE & SECTOR CONFIGURATION FOR SELECTED INTER-SITE DISTANCES.

Minimum ISD filter	**All (0 km)**	**2 km**	**4 km**	**6 km**
Sites	319	232	170	117
Sectors	920	667	495	328
Avg. ISD, 1 neighbor [km]	2.8	4.3	6.2	8.6
Avg. ISD, 3 neighbors [km]	4.1	5.6	8.9	11.1
Supported deployment at 1 % outage (I: indoor, O: outdoor)				
LoRa	I 10 dB	I 10 dB	I 10 dB	I 10 dB
SigFox	I 20 dB	I 20 dB	I 10 dB	I 10 dB
NB-IoT	I 20 dB	I 20 dB	I 10 dB	I 10 dB
GPRS	O	O	None	None

covered, besides 1 % of the GPRS devices, while the other RATs have outage of up to about 3 % for the indoor device locations with 20 dB additional penetration loss, which means that Telenor's coverage is very good in the rural area. The NB-IoT RAT supports the highest MCL of 164 dB and therefore less than 10 % of the deep indoor, rural device locations are in outage. SigFox and LoRa have slightly worse link budgets with MCLs of 160 dB and 157 dB and therefore outage of 15 % and 24 % respectively.

Fig. 4 shows the combined outage statistics for both urban and rural device locations. There are about 5 times more rural than urban device locations and therefore the overall result is dominated by the rural performance. All technologies provide outdoor coverage and also light indoor coverage except for GPRS, which has 8 % outage. SigFox and NB-IoT provides an outage below 1 % for the device locations with 20 dB additional loss, while LoRa has 2 % outage. For the deep indoor use case NB-IoT has 8 % outage, while SigFox and LoRa have 13 % and 20 % outage respectively. To summarize the deployed network has very good coverage for the typical indoor device location, experiencing up to 20 dB additional penetration loss, whereas the deep indoor location is challenging to reach for all the studied RATs.

Up to this point the presented results have been based on the original site deployment made by Telenor and virtually upgraded to the studied technologies. However, from a cost perspective, it is interesting to study the outage probabilities if not all sites are upgraded. Table III provides an overview of the number of sites and sectors when applying a minimum ISD filter to the original deployment (denoted *All* in the Table). As the filter is applied the number of sites and sectors is reduced e.g. almost to half the original number for the 4 km filter going from 319 sites to 170, but the average ISD for the nearest neighbor is also more than doubled from 2.8 km to 6.2 km. The Table also contains the supported deployment at 1 % outage for the four technologies. Further details are available in Fig. 5, which contains the outage probabilities as a function of the minimum ISD filter. As expected NB-IoT performs the best

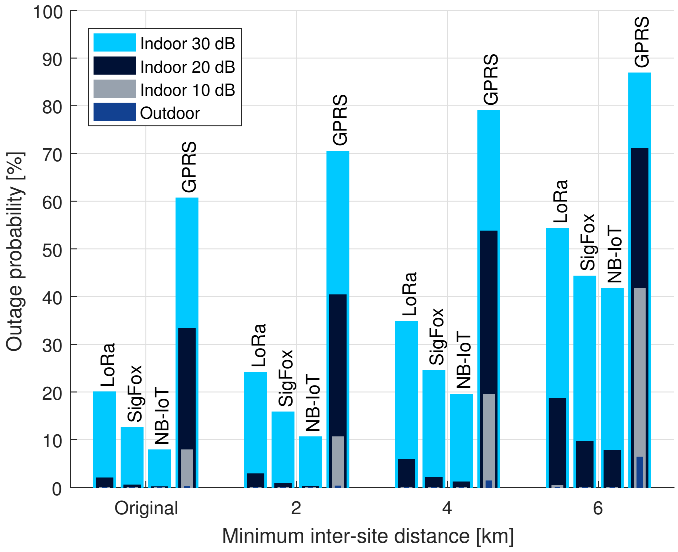

Fig. 5. Outage probability for rural and urban device locations in the North Denmark region.

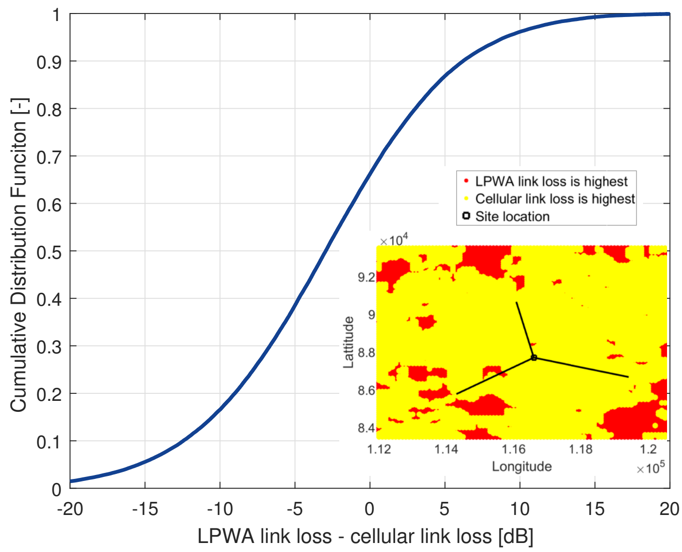

Fig. 6. CDF of the difference between LPWA and cellular link loss for the original deployment in both rural and urban areas. The inserted figure is an example of the link loss at a specific site. The black lines indicate the main bearing of the cellular site.

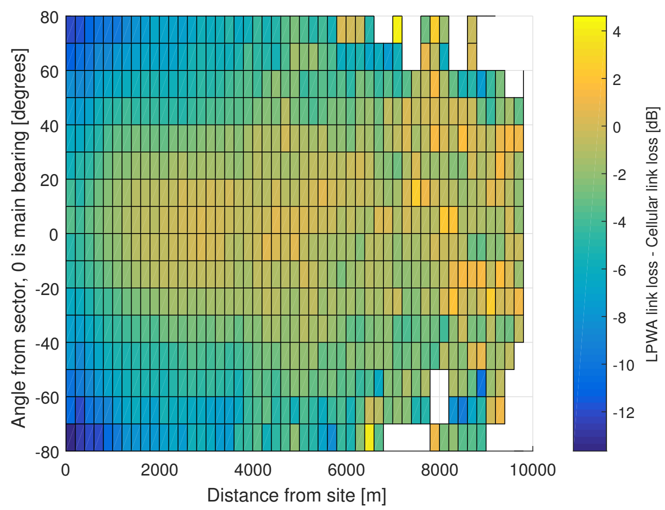

Fig. 7. Comparison of cellular and LPWA link loss as a function of angle from main bearing and distance from site. Data is averaged for all 920 sectors in the original deployment. Only device locations where the serving site is the same for the LPWA and cellular site is included in the analysis.

independent of the minimum ISD filtering, and up to a filter of 4 km the indoor 20 dB additional penetration loss outage is well below 5 %. SigFox also provides good coverage for most deployments, but for the 6 km filter the outage exceeds 10 % for the 20 dB penetration loss device locations.

The three link loss figures 2, 3, and 4 all show that the LPWA devices experience slightly lower link loss as compared to the cellular devices. The difference between the link loss of the LPWA and cellular device locations is illustrated in a CDF in Fig. 6 and the average is about -3 dB. The inserted figure in Fig. 6 shows the areas where either LPWA (red) or cellular (yellow) link loss is highest for a specific site in the area. Note that devices may not exist in every pixel of that area, depending on the presence of house numbers. The reason for the difference is that the omnidirectional antennas of LPWA provide better coverage for device locations which are at the sidelobes of the cellular sector's antenna's main bearing. This is visible in the inserted figure in Fig. 6 where red areas (higher LPWA link loss) mainly are found far from the site at the end of the main bearing, while yellow areas (higher cellular link loss) are located close to and around the site. This is further illustrated in Fig. 7, which shows the link loss difference between LPWA and cellular as a function of the main bearing of the cellular sectors' main bearings and the distance to the site. The data in Fig. 7 is averaged for all sectors in the original deployment. The figure illustrates the cellular antenna has a higher gain and thus provides better coverage in the direction of the main bearing and far away from the site, on average providing 2-4 dB lower link loss. In addition, Fig. 7 clearly shows the advantage of the omnidirectional antenna at the sides of the sector where the LPWA link loss can be 10-13 dB lower than the cellular link loss.

IV. Discussion

In this work the minimum ISD was used to only perform a partial upgrade of the deployed network. From a cost perspective it obviously reduces the price, especially if a certain site not only requires a software upgrade, but also new hardware. Even though the degradation from the original deployment to filtering with 2 km ISD is not significant the interference pattern may change significantly for NB-IoT. The reason is that sites, not upgraded with NB-IoT, may continue transmitting the legacy LTE signals in the physical resources which are designated for NB-IoT in the upgraded sites. This will result in increased interference, which may degrade the performance more than the degradation due to lower coverage probability [7]. However, this will not be the case for the LPWA technologies since there are no legacy

LoRa and SigFox sites. Therefore it is especially interesting to note that SigFox provides an outage below 5 % for the indoor device locations with 20 dB additional penetration loss both for the original deployment and when filtering with 2 and 4 km. According to Table III the number of sites is almost reduced by half from 319 to 170 and this will result in significant cost savings when deploying a LPWA network.

Besides the required coverage the systems must also have sufficient capacity in order to support the devices' traffic requirements. Therefore it may be necessary to deploy more sites than what this coverage study suggested. In this respect the sectorized NB-IoT has an advantage since the physical resources are reused within the (usual) three sectors of a site, while the omnidirectional LPWA systems do not have this option. In future work we will study the capacity of the four systems in further detail. In addition, it will also be interesting to study how small cells or WiFi access points located indoor can improve coverage and capacity for IoT devices.

Related to the results on LPWA versus cellular coverage at the same device locations, it is important to remember that Telenor deployed the network to cover large villages, cities, and the major infrastructure e.g. motorways and highways. Therefore, the sectors at a site may not be distributed equally with 120 degrees spacing in the horizontal plane and this is another reason why the omnidirectional antenna provides better coverage for certain locations as indicated in the CDF of Fig. 6. However, in practice the sectorized antennas point towards the areas where the most devices would be located and thus the highest capacity demand. Furthermore, LoRa and SigFox have a worse link budget, see Table I, and therefore NB-IoT has better coverage probability even though the average link loss is higher for NB-IoT.

A final key point for future work is to study the interference generated in the systems. A short ISD may result in more interference, if the sector bearings and antenna tilts are not planned well. In addition, as listed in Table I, the LoRa and SigFox technologies rely on unlicensed frequency bands and therefore they may also be subject to interference from other devices such as remote car keys, baby alarms, smoke detectors, and various industrial applications [14].

V. Conclusion

In this work the geographical coverage probability is simulated for the long-range, low power wireless Internet of Things technologies GPRS, NB-IoT, LoRa, and SigFox in a 7800 km^2 area with 10 cities and large rural areas.

The network deployment is based on the local operator Telenor's configuration of 2G, 3G, and 4G sites. Only the sites with sub-GHz carriers are utilized, and in the simulations the 319 sites are virtually upgraded to support the studied technologies. In order to determine the dependency on deployment strategy the minimum Inter-Site Distance is varied from including all original sites to 6 km.

Independently of the Inter-Site Distance the NB-IoT provides the best coverage probability even though the devices experience a link loss, which on average is 3 dB higher than the LoRa and SigFox deployments that rely on omnidirectional antennas. All technologies provide less than 1 % outage for outdoor devices, located in areas with a house address, while GPRS has 8 % outage for light indoor devices, who experience 10 dB additional penetration loss. For indoor devices with 20 dB additional penetration loss LoRa has 2 % outage, while SigFox and NB-IoT still provides less than 1 % outage due to their large supported Maximum Coupling Loss of 160 dB and 164 dB, respectively. For the deep indoor devices, experiencing 30 dB additional penetration loss e.g. due to a location in a basement, NB-IoT performs the best, but has an outage of 8 %. SigFox and LoRa provide 13 % and 20 % outage, while GPRS cannot provide coverage for more than 60 % of the device locations.

Increasing the minimum Inter-Site Distance to 4 km reduces the number of sites from 319 to 170, but NB-IoT and SigFox are still able to provide less than 5 % outage for all outdoor devices and indoor devices experiencing up to 20 dB additional penetration loss. However, NB-IoT may experience significant interference from legacy LTE systems utilizing the same resources, while SigFox may encounter capacity problems. These topics are planned future work in addition to studying interference in the unlicensed bands, which SigFox and LoRa share with many other systems.

Acknowledgment

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